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PASSIVE RESEARCH AND PRACTICE*

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ABSTRACT

Passive-solar applications in buildings are described and examples are given to illustrate how research in the field has been approached. The major emphasis of the research has been on devising mathematical models to characterize heat flow within buildings, on the validation of these models by comparison with test results, and on the subsequent use of the models to investigate the influence of both various design parameters and the weather on system performance. Results from both test modules and monitored buildings are given. Simulation analysis, the development of simplified methods, and systems analysis are outlined. Passive-solar practice is described and the key elements that have led to successful passive-solar applications are discussed.

KEY WORDS

Passive Solar, Research, Test Modules, Monitored Buildings, Systems Analysis.

HISTORICAL PERSPECTIVE

Although passive solar applications in buildings have been extensively practiced by several different civilizations over the period of human history, modern interest in passive solar heating is quite recent, starting in the early 1970s. The number of passive solar installations has grown incredibly from a half dozen to well over 100,000 in 10 years; most are located in the United States. We are now seeing major interest developing in many other countries throughout the world, notably in France. It is certainly conceivable that within 10 years most new construction within the United States will utilize passive solar techniques for heating, and that this trend will become worldwide, especially in the more temperate climates.

It is interesting to note that much of this development has taken place without the aid of a strong research program. Although passive systems developed in parallel with active systems, a large research budget stimulated active system development whereas minimal funding was devoted to passive system research. The reasons for this dichotomy are many and we will not belabor them here, but its existence is a matter of record. Even when government funding did materialize, it was directed largely toward commercialization activities rather than research.

This historical difference has strongly colored the development of passive solar compared with active solar systems. Passive solar heating has developed as a grass roots technology in which designers transfer concepts into practice, not only without the benefit of sophisticated experiments or detailed numerical analysis, but often without even the most rudimentary engineering calculations. In this regard, passive solar heating development has been more characteristic of the building industry as a whole than of the engineering industry. This process has not necessarily been detrimental to the orderly development of passive solar techniques. Much of the evolution has focused on intangible issues that are not particularly conducive to a research-oriented analysis. These issues include concerns about aesthetics, marketability, and the integration of passive solar construction techniques into the infrastructure of the

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conventional building industry. Passive solar buildings are quite forgiving of design variations and flaws; most such buildings have worked quite well, requiring a fraction of the heating requirements of conventional buildings, and their owners have been quite satisfied.

Examples of early research on passive solar heating are rare and isolated. Researchers such as Dietz [1] at MIT and Neubauer [2] at the University of California at Davis conducted a few experiments, but the results of these were neither widely known nor appreciated. A patent was taken out by E. M. Morris [3] in 1898 for a thermosiphoning air panel, but there was no quantitative prediction or evaluation of performance.

This is not to say that there had not been significant efforts put to the thermal evaluation of buildings. Quite the contrary; major efforts in many countries were devoted to evaluation of building materials and the analysis of heat flow through building elements. This work laid an important foundation for passive solar research today. However, it cannot be considered passive solar research in itself because of several characteristics: (a) solar gains were usually regarded as a nuisance, (b) heat storage in building elements was treated peripherally, if at all, (c) the emphasis of the investigation was to provide equipment sizing information, and, most importantly, (d) the results were rarely used to guide building design toward better use of natural energy flows.

Passive solar heating research really began in the 1970s in direct response to passive solar designs that had been built. The three early buildings of greatest significance are the Wallasey School [4] by Morgan in England, the Trombe house [5] in France, and the Atascadero house [6] by Hay in California. Each was analyzed and evaluated by a team not associated with their construction. M. G. Davies and A. D. M. Davies analyzed the Wallasey School from a thermal and a sociological standpoint, respectively.[7] J. F. Robert, M. Cabanet, and B. Sesolis [8] evaluated, but did not analyze, the Trombe house (Robert lives in the Trombe house). Prior to its construction, Yellott and Hay had built and evaluated a test structure based on the Skytherm© principle.[9] Following the construction of the Hay house in Atascadero, California, Niles and Haggard [10] analyzed and evaluated its performance. Significantly, both Davies and Niles used thermal network simulation analyses to investigate the dynamic behavior of heat flow in the structures. However, even in these cases, the work was confined to an investigation of the particular building in its particular climate, and no attempt was made to generalize the results.

The turning point for passive solar research was the first passive solar conference in Albuquerque in May 1976.[11] Much of the early research work was reviewed, and most of the individuals who have subsequently contributed to the research effort were present. Since that time, national passive solar conferences, sponsored by the American Solar Energy Society, have served as the focal point for the presentation of research results.

RESEARCH ISSUES

Research into the thermal behavior of buildings is an old and established field, and much of the information developed is directly applicable to passive solar buildings. However, in a passive solar heated building the thermal impact of solar on the building is enhanced to a point where it becomes the dominant thermal factor. Thus, what was a minor part of the building energy balance becomes major, and new analysis tools are needed. Also, new elements of the building may be added, such as Trombe walls or sunspaces, and these must be characterized. Accurately understanding the storage and distribution of solar heat within the building becomes essential. Whereas much early work unrealistically characterized the building inside temperature as constant, reasonable variations are always allowed, greatly enhancing the natural heat storage and distribution possibilities with major reductions in auxiliary heating and cooling requirements.

A second use of natural energy that augments passive solar heating is daylighting. This is particularly important in commercial buildings where the current practice of excessive use of artificial lighting leads to huge internal gains, which, in turn, lead to large cooling requirements. By use of natural lighting, not only is the lighting electricity saved, but electricity needed for cooling is greatly reduced. Because natural lighting requires windows, the building heat loss may increase. Also, there is less internal heat. The combined effect may well signal the need for passive solar heating. Thus, window location for daylighting should follow practices developed for passive solar heating; the use of south-facing windows and clerestories becomes as a main strategy. What might have been an internal-load-dominated situation evolves into a more skin-dominated load building requiring much less operating energy. The already highly complex process of designing commercial buildings becomes even more involved when daylighting is considered and new analytical tools are needed. Daylighting is also an important factor in residential buildings, even though it has always been taken for granted.

Natural cooling is perhaps the most complex passive research area because the building is thermally opened to the surroundings at times to encourage rejection of heat. Night ventilation of the building is usually the most important passive cooling strategy and the one least tractable to analysis. Radiation cooling is analyzed more easily and has been more carefully researched. Earth contact cooling, although of minor importance, has also been the subject of much investigation.

RESEARCH DIRECTIONS

The main focus of research in passive solar heating has been on the performance evaluation of buildings. Knowledge gained through the understanding of the behavior of existing buildings can be used both to predict the performance of future buildings and to devise strategies to make them more effective. Thus, a major emphasis of the work has been threefold: (1) development of mathematical models that characterize heat flow and thus thermal behavior, (2) the validation of these models by comparison with test results, and (3) the subsequent use of the models to investigate the influence of both various design parameters and weather characteristics on performance.

This explanation illustrates how analytical modeling work has become the cornerstone of the research effort. This relationship is shown clearly in the schematic diagram of Fig. 1, which shows the key elements of the research program and the relationship between those elements. The logical progression of activity flows from left to right in this schematic, beginning with experimental results obtained in test modules, special experiments, or monitored buildings. Based on these results and known physical principles, analytical models are developed and validated. Using weather and solar data from a particular locality, the analytical models can then be used to predict performance in a variety of climates for a variety of proposed designs. The models can also be used for sensitivity analyses, to develop simplified prediction methods, and to explore the relationship between passive solar and conservation strategies. Results are published both in technical papers and as user-oriented manuals.

EXPERIMENTAL RESULTS

Test Modules

Small test modules play an important role in passive research. Quite a large number of special-purpose test modules have been built to obtain data under carefully controlled conditions. Efforts in the US are reviewed by Moore.[12] The units serve three major purposes as follows:

- Direct side-by-side comparisons of various competing strategies.
- Obtaining data for the validation of computer codes.
- Special component tests.

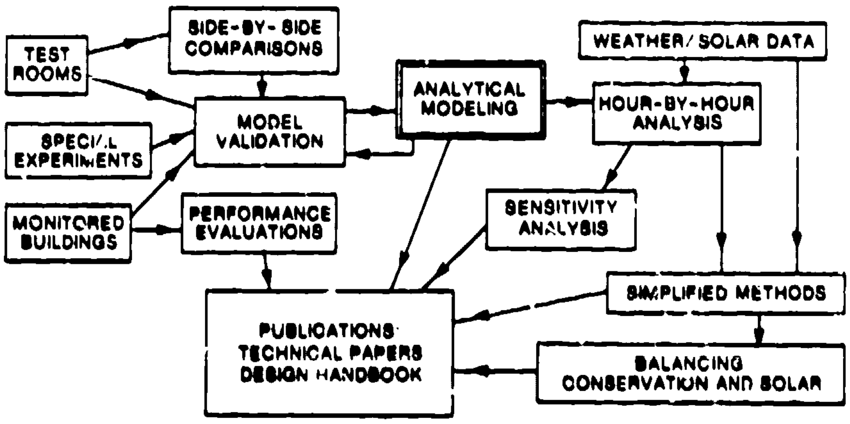

Fig. 1. Schematic of the key elements of the research program.

Test modules are sometimes operated free running, that is, without auxiliary heat. More commonly, they are operated with a thermostatically controlled inside environment. This allows a more direct comparison between units and yields a more realistic operating profile.

Three sizes of test units have been built: test boxes, usually about 1 m (3 ft) on a side; test rooms, usually about 4 m^2 (40 ft^2) in area; and larger test buildings, which may have more than one room. Two examples of the results of recent test room work at Los Alamos are shown in Figs. 2 and 3.

Figure 2 shows test room performance for 1 day.[13] This illustrates the rather dramatic differences in the thermal comfort characterisitics of the different test rooms. The rooms were thermostatically controlled to 23.9°C (75°F). Note that the direct gain test room, which has an inadequate mass-surface to glass-surface area ratio of 3:1, uses about the same back-up heat as the unvented Trombe wall; however, the thermal comfort characteristics of the

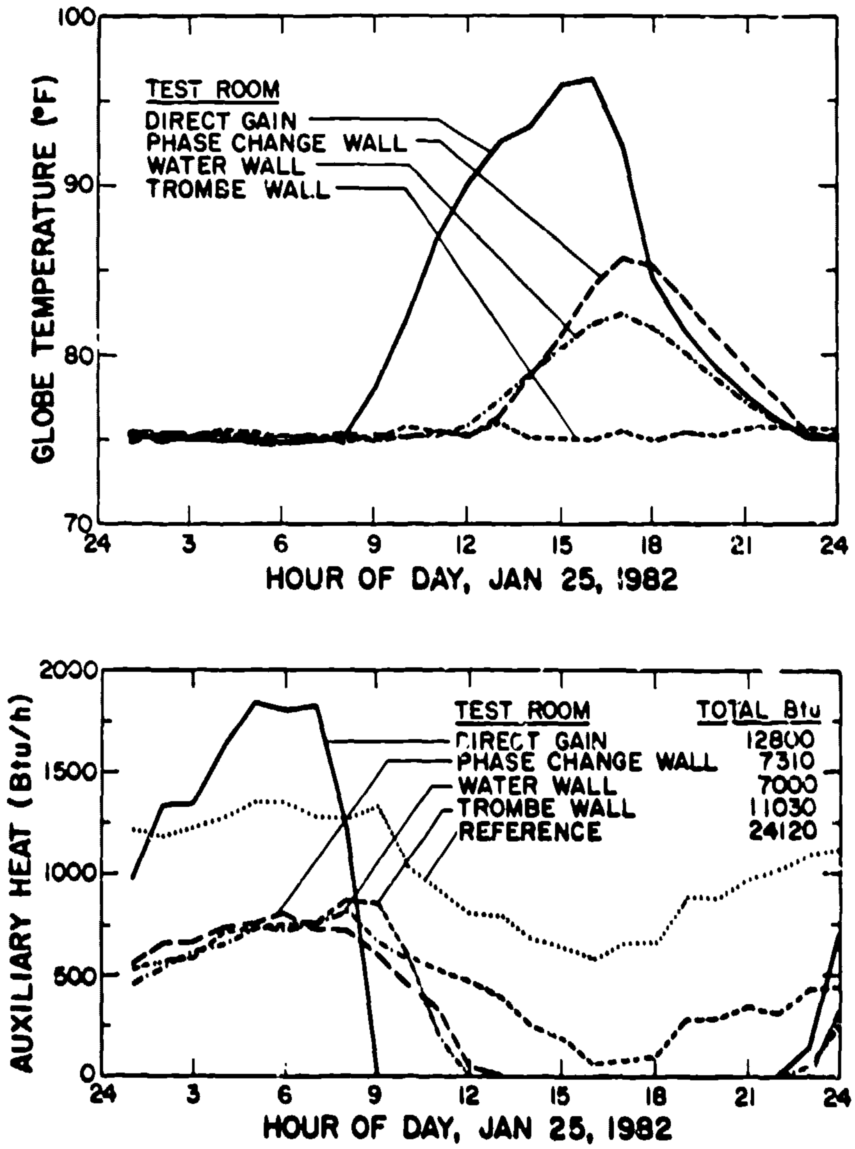

Fig. 2. Temperatures and powers measured during one sunny day in five controlled test rooms. The net load coefficient of each room is 13.7 W/°C (624 Btu/°F-day). The average outside temperature is approximately 4.4°C (40°F).

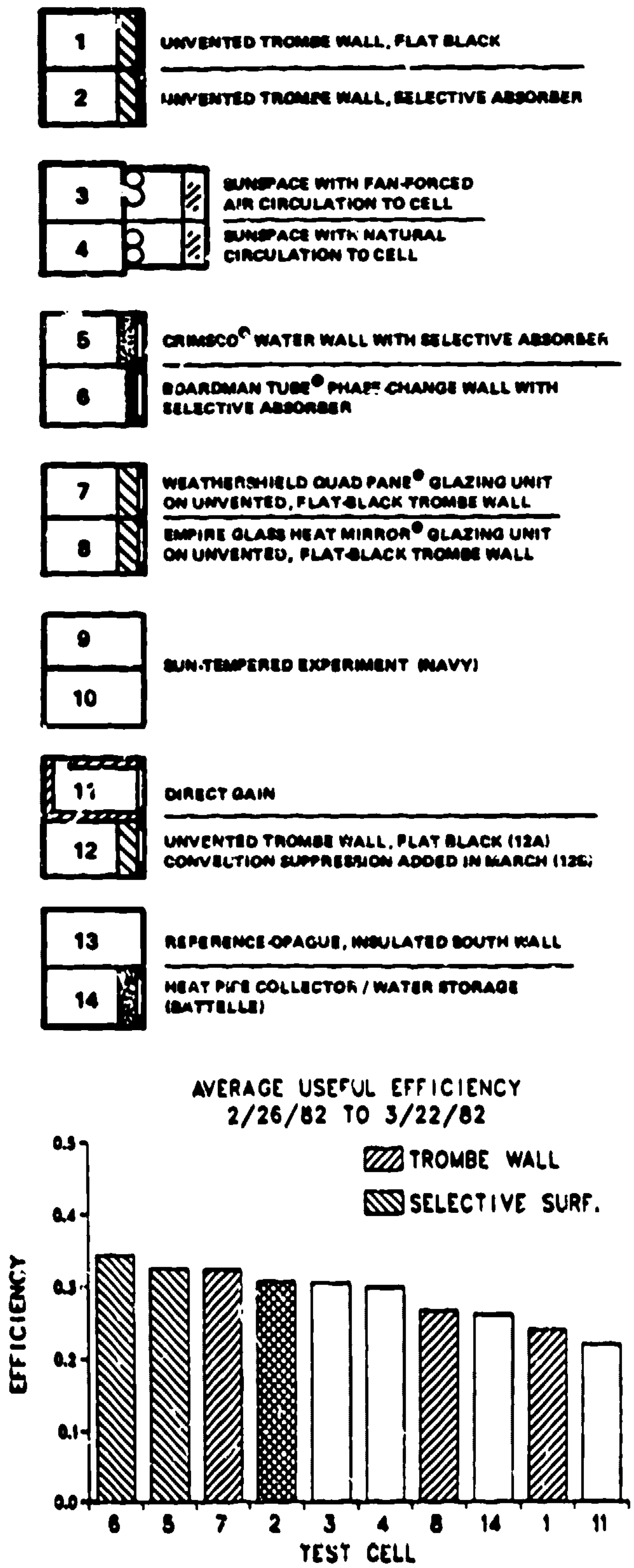

Fig. 3. Test cell configurations and performance for the 1981-82 winter.

two are radically different. The thermal performance of the phase change and water wall rooms are quite comparable; both have selective surfaces.

These results are taken during a sunny day. To get a more accurate picture of long-term performance, it is appropriate to integrate the results over several weeks. Figure 3 shows comparative useful efficiencies of various test room configurations over a 25-day winter period in Los Alamos.[14] The average outside temperature during this period was 3.7°C (38.7°F). The rooms each have the same glazing area and building load coefficient and were thermostatically controlled to 18.3°C (65°F). Useful efficiency accounts for only that energy required to maintain the building up to 18.3°C (65°F) and discounts energy associated with building temperatures in excess of 18.3°C (65°F). From these results, one can see (1) the great effectiveness of a selective surface on the outside of a Trombe wall or water wall; (2) that a heat mirror glazing does not significantly increase performance whereas a multilayer, high transmission glazing makes a significant improvement; (3) that natural convection from a sunspace to the adjacent room is about as effective as forced convection; and (4) that phase change materials can be quite effective as a thermal storage wall (although many of the phase change containers tested at Los Alamos have shown mechanical failure).

Moore's report identifies 77 test rooms and 31 test buildings in the United States. They have value not only in providing experimental data to the research community, but in demonstrating the effectiveness of passive strategies in different climates and serving as learning tools to students in a university environment.

MONITORED BUILDINGS

Numerous passive solar buildings have been monitored by various researchers with generally encouraging results. The main programs have been those at Los Alamos, where 15 buildings were monitored; the National Solar Data Network (NSDN), which also monitored about 15 passive solar buildings; the Class B Monitoring System at the Solar Energy Research Institute (SERI), which currently has about 75 buildings under study, and a Class B monitoring program in California conducted by the California State University, which has monitored 11 buildings. In addition, numerous individual researchers have undertaken the monitoring of one or more structures.

To obtain an overall picture of the results, we have taken data from 48 of these monitored buildings and presented the performance in a consistent format. The performance measure chosen, although far from perfect, does give a general comparative idea of the effectiveness of the various buildings. The results are shown in Fig. 4. Energy consumption by the building is divided by the floor area and also by the heating degree days. This normalization puts the various buildings on a reasonably comparable basis. Three types of energy are distinguished: internal energy (due to lights, people, and appliances), auxiliary heat, and solar gains.

The general conclusions that follow from a study of these and other results of monitored buildings are as follows:

- Building heat load coefficients in the range of 0.83 to 1.53 W/°C m^2 (3.5 to 6.5 Btu/°F day ft^2) are routinely achieved, although much larger values are observed for a few buildings. The results underline the importance of good conservation practice.
- Auxiliary heating requirements as low as 0.24 to 0.48 W/°C m^2 in sunny climates (1 to 2 Btu/°F day ft^2) are achievable. Values of 1-1/2 times these levels are routinely achieved.
- Good overall performance is not especially correlated with climate, although there is some tendency for the solar performance to be better in sunny climates.
- Internal heat varies widely and, in some cases, makes a major contribution.
- Solar fractions of 50% or greater are often achieved. In some cases the solar performance is illusory because losses from the glazing probably equal or exceed solar gains. It is estimated that the solar savings exceeds 50% of the total load in 20 of the 48 buildings.

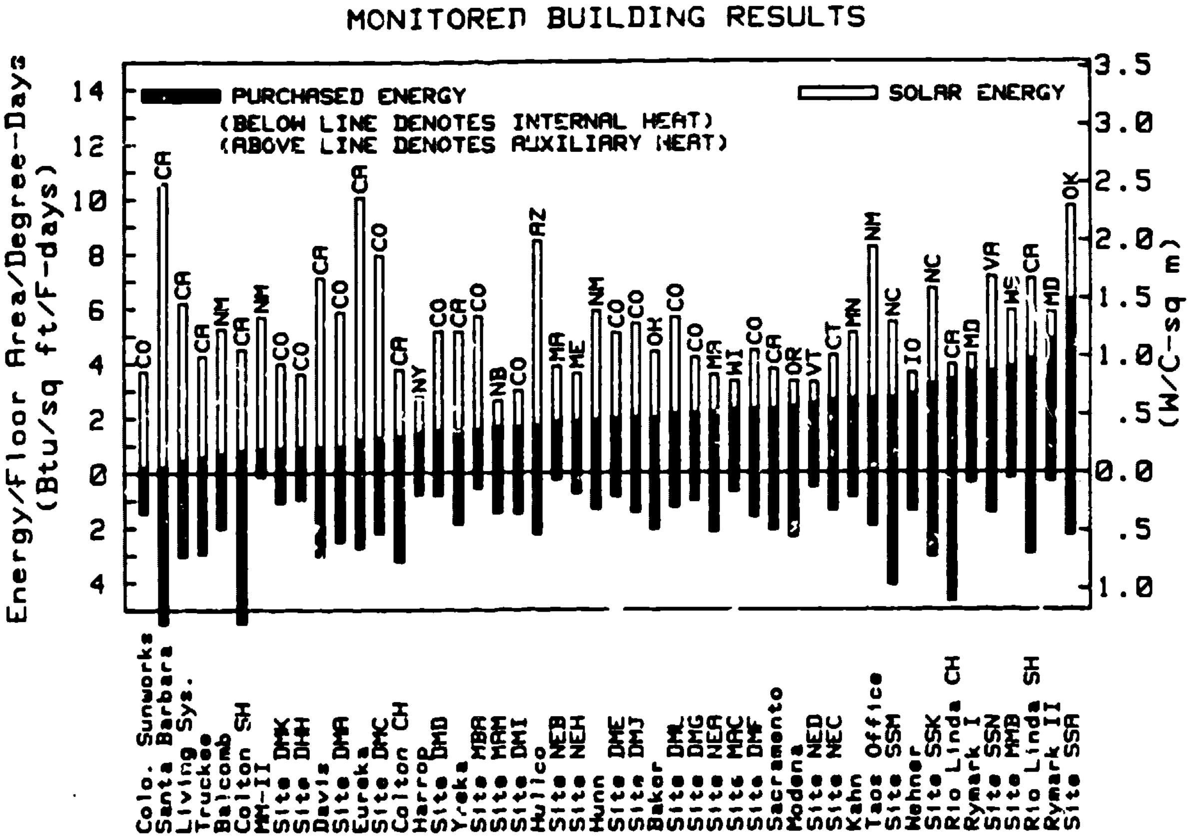

Fig. 4. Results of the monitoring of several buildings. The bars show seasonal energy (usually for 5 or 6 months) divided by the building floor area and the actual degree days for the season, calculated for a base temperature of 18.3°C (65°F). The black portion of the bar denotes purchased energy; the portion below the bar is internal energy, and the black portion above the bar is auxiliary heat. The total length of the bar is the total heat required by the building, determined using the building heat load coefficient and the measured inside/outside ΔT integral. Thus, by subtraction, the white portion of the bar is the solar energy absorbed less any vented energy. The state in which the site is located is indicated above the bar. The buildings are rank ordered according to auxiliary heat. Several buildings with low internal heat were unoccupied but were thermostatically controlled to normal levels.

- Other benefits should also be considered. For example, the daylighting benefit in the Taos State Office Building reduces the need for artificial lighting by at least 60%. This explains the moderate internal heat observed, which is very low for an office.
- Proper site selection and passive collector orientation are very important to good performance. Some systems demonstrating the worst performance are those that are sited incorrectly.
- Movable insulation can notably improve performance and is especially valuable in colder climates. However, if manually operated movable insulation is used, it must be convenient, easy to use, reliable, and kept in good working order.
- No particular passive system type emerges as the best performer. Good thermal design, however, is essential.
- The overall need for purchased energy is far less than that of typical buildings in all but 2 of the 48 buildings included in Fig. 4.

- Many valuable lessons can be learned from a thorough review of monitored building data. Although not detailed here, both positive and negative factors, which could be reinforced or solved by better design, are uncovered in virtually every instance.

- An important deficiency of monitoring is the determination and reporting of the quality of the indoor environment created. Comfort indices should be given. Also, lighting, humidity, ambiance, and convenience should be evaluated.

MATHEMATICAL MODELING

Thermal Networks

The response of a building to any schedule of heat input is simulated by solving a set of differential equations that describe the heat flow from point to point within the building. One must first select a reasonably small set of elements within the building whose temperature will be calculated. Elements that can be expected to be about the same temperature can be lumped together into one element. It is of particular importance to include all of the important heat-storing mass within the building in one or another of these mathematical elements. Massive portions expected to be at rather different temperatures should be characterized as different elements.

Having made this selection, the analyst then writes an ordinary differential equation describing the heat balance for each element. This heat balance includes heat flow to neighboring elements by radiation, conduction, or convection, solar energy inputs, and other heat inputs. This set of differential equations can then be solved as an initial value problem with several independent variables including solar gain, outside temperature, and thermostat setting. Auxiliary heat input is adjusted to maintain a desired temperature of one or more of the elements (the room air temperature is usually the controlled element).

Other Analysis Approaches

Another standard approach to building energy analysis has been the use of weighting functions or transfer functions (these are not to be confused with Laplace transforms or Fourier analysis). Because the heat flow through a wall is generally assumed to behave according to a set of linear equations, the response on one side can be characterized as a convolution of the inputs on the other side. The convolution is an integral, usually performed as a summation, of the input at each previous time interval multiplied by a weighting function, which is essentially the response of the wall to an impulse input. The technique is described in mathematical detail by Muncey.[15] Both the inputs and outputs can be either temperatures or heat fluxes.

The weighting-function approach has been used in most large-building analysis codes because it is particularly amenable to the handling of lightweight frame construction walls that may have considerable structural detail. The weighting functions can be precalculated, incorporating as much detail about the wall as desired, and entered into a table to be used throughout the rest of the calculation. Generally there are only a few weighting-function points because the time reponse characteristic of the wall is fairly short. For massive walls, this computational advantage is not so pronounced because the number of weighting functions becomes much larger; in terms of computational efficiency, thermal network analysis then becomes more competitive.

Weighting-function analysis is particularly convenient when the inside temperature is held constant; however, if it is allowed to float, account must be made with another set of weighting functions, increasing the computational complexity. By contrast, thermal network analysis is hardly more complex for a floating inside temperature than for one that is fixed.

Harmonic analysis, another computational technique that has been used by several analysts and researchers, provides yet another way of solving the same set of differential equations.[16,17] The Fourier or Laplace transform of each equation is computed, and the equations are then solved algebraically in terms of the Laplace operator. Time solutions can be obtained by inverse transformation. Used to calculate the time response of a building, this approach has been primarily used by afficionados of the technique; it offers no particular computational advantage over network techniques.

The primary disadvantage of harmonic analysis techniques is their inappropriateness in cases where major nonlinearities exist. Although methods of dealing with nonlinearities have been developed, they are both awkward and complex, and this offsets any advantage of harmonic analysis. For smoothly varying nonlinearities such as radiation heat flow, the equations can easily be linearized around the operating point; the inaccuracy implied by this process is trivial for the size of temperature swings that would usually be experienced. An example of the type of nonlinearity that cannot be accommodated is the off-on character of a thermostat; therefore, harmonic analysis is not very suitable for determining auxiliary heat requirements.

The primary advantage of the Fourier transform approach is in investigating the response of the system at a particular frequency. The frequency of greatest interest is the 24-hour cycle (the diurnal cycle) because it is such a dominant and important part of the weather input. By such techniques one can easily study the clear-day temperature swings to be expected inside the building.[18,19]

SYSTEMS ANALYSIS

Systems analysis includes four types of analytical investigations: the first is the systematic study of how climate affects passive solar heating performance, the second is the study of how changes in design parameters affect system performance in a particular locality, the third is the development and use of correlation techniques as a simplified method of performance estimation, and the fourth is the development and use of a methodology for determining the optimal mix between conservation and solar strategies.

The Effect of Weather on Performance

Once a simulation model has been developed for a particular building configuration, it can be run using hourly weather input data for any location where such data are available. Within the United States, for example, there are 35 sites where weather data, including solar data, have been taken and compiled by the US Weather Service. In addition, based on correlations developed from this primary data set, hourly solar data sets have been generated for some 240 sites where hourly temperature and other weather data have been taken (these are called ersatz data). This enormous data set is available from the US Weather Service (National Oceanographic and Atmospheric Administration, Asheville, North Carolina) in a variety of computer-compatible media. It is easy to see that one is limited more by the time and cost of doing computer simulations than by available data. To study the effect of weather on performance, simulations are run for each site for each configuration of interest.

Simplified Methods

It is now generally accepted that computer simulation will give an accurate representation of the performance of passive solar buildings, a condition that makes simulation a desirable design tool if the designer has the equipment, the capability, and the inclination to take this approach. But even under the best of circumstances, it is costly and time consuming. Most designers ask for simpler techniques that are amenable to the use of hand calculators or desk-top microcomputers on which estimates can be generated in a few minutes.

Correlation techniques that meet these requirements and give reasonable accuracy have emerged as practical procedures. These methods are particularly useful early in the design process when quick feedback is essential; they can be applied to either residential or commercial buildings. Both a monthly calculation--the solar load ratio (SLR) method--and an annual calculation--the load collector ratio (LCR) method--have been developed. The annual method uses tables precalculated by the SLR technique and is more appropriate to hand analysis, whereas the monthly method is more versatile and is more appropriate to programmable calculator or microcomputer-aided analysis. Both are described in Refs. [20], [21], and [22].

Deciding Between Conservation and Passive Solar Options

A technique has been developed to determine the optimal mix between conservation and solar strategies.[22,23] To obtain an answer, one needs the cost characteristics of both the passive solar system and the energy conservation features. This information will generally be in the form of the cost per R per unit area for the wall and ceiling insulation, the cost per additional glazing for windows, the cost of reducing infiltration (including the cost of adding an air-to-air heat recovery unit if needed), and the cost per unit area for the passive solar collection aperture. Given this information, the method provides simple equations that can be used to trace the economic optimal-mix line for a particular locale.

LARGER BUILDING ISSUES

In large buildings the energy situation is often much more complex than in smaller buildings because internal energy generation by lights and equipment often provides much of the energy required for heating and also because of the multizone character of many large buildings. The energy issues in the building may be dominated by cooling requirements instead of heating; moreover, the operation and control of the heating, ventilating, and air conditioning equipment may well be quite complex and significantly alter the overall energy-use pattern of the building. The following issues are of particular importance.

Daylighting

Use of natural light during the day can significantly reduce not only the requirements for artificial lighting, but somewhat reduce the cooling requirements because of the higher efficiency of daylighting. The type of analysis necessary to treat daylighting has dissuaded most practioners from attempting to use numerical methods for design because of the complex geometries that are typical of most buildings. However, a number of specialized techniques have been developed, and ongoing work will probably result in development of suitable analytical methods. Many of the methods that have been developed are suitable only for diffuse sky conditions.[24]

The most widespread design technique is now and probably will remain the use of scale models. These are relatively easy to build, quite representative of full-scale conditions, and give both qualitative results (such as evaluation of light quality) and quantitative results.

Balancing

Thermal balancing of a building must be done both on a space-to-space basis and also on a time-of-day basis considering patterns of internal heat generation and occupancy. Mismatches between the availability of natural energies and the building's energy needs may result in the need for transporting heat from space to space and for providing auxiliary heating and cooling energy, perhaps at the same time.

Analysis Methods

Because both building configuration and energy issues tend to be complex, analysis codes for large buildings must be complex. The major computer programs that exist have evolved out of earlier codes and utilize weighting-function analysis techniques. They contain large libraries of materials properties, standard wall sections, and subroutines that characterize heating, ventilating, and air-conditioning systems. Great effort has gone into making the building description as architectural as possible, leaving the translation into mathematical terms to special routines within the program.

Input to the computation consists of hourly measurements of weather and solar parameters for a location of interest. Output consists of building energy consumption, which is generally summarized according to a number of different user-specified options. The programs require large computers and a very sophisticated user.

PASSIVE PRACTICE

In a remarkably short period of time "passive solar" has become part of the vocabulary of building desigers, buyers, realtors, financiers, and researchers. Coined by B. T. Rogers in the early 1960s, the word "passive" was intentionally chosen to emphasize an alternative approach to the then-popular active solar technique.

Because it employs conventional building materials and because the basic concepts are easily understandable, passive solar has found relatively easy acceptance among designers and builders. In addition, there are two important groups of building material manufacturers who have embraced passive solar as an important strategy to improve their position in the building marketplace. These are the glazing industry and the masonry industries. In both cases, the increased importance of conservation techniques within the country and the tendency toward adoption of ever more stringent building regulations have tended to reduce the use of both glass and mass within the buildings because both have poor insulating properties. However, this energy disadvantage can be turned into an energy advantage when one considers passive solar. Glass, properly used, enhances both winter heating and daylighting. Mass is essential to the storing of passive solar gains and is also very helpful in the reduction of cooling loads during seasons when the temperatures frequently cross the comfort zone. Thus, there are natural constituencies that have endorsed passive solar, greatly speeding its dissemination across the United States.

Another factor that has enhanced the diffusion of passive solar in the marketplace is, ironically, the extremely slow market conditions that beset the building industry beginning in 1979. Whereas building was previously a seller's market, with builders able to sell nearly anything, the downturn in market conditions resulted in a buyer's market, with a much more selective buying public. Concern over energy efficiency in buildings has become a major issue with potential buyers, and passive solar, as a visually obvious indication of energy efficiency, has become an effective market strategy. In a fiercely competitive situation, it sometimes makes a difference in the marketability of a building.

Adoption of passive solar has been on a very regional basis. Characteristically, interest begins in a specific locality, such as Santa Fe, New Mexico; Davis, California; Raleigh, North Carolina; Portland, Oregon; upstate Maine; and Kansas City, Missouri. As a real estate product, passive solar is highly subject to acceptance and concurrence with local market conditions. Typically, once acceptance is achieved, diffusion occurs outward from these centers. Normally there is a hopscotch effect with the more progressive areas adopting a few passive solar buildings early and the more conservative areas following in due course. Although climate is an important determining factor, the willingness of the local population to try a new approach is equally important. Once the credibility of passive solar is established in an area, its dissemination outward begins. Passive solar is a very experiential commodity and the marketplace relies on first-hand experience for diffusion.

Residential Practice

The results from monitored buildings give testimony to the fact that passive solar buildings work well. This is essential if they are to survive in the marketplace, but good performance alone is not sufficient. Clearly, many other factors must also be correct for passive solar buildings because they have already proven themselves in the marketplace. At a time when energy consciousness has become a key priority for the house-buying public, passive solar provides visible testimony that good energy performance has been a design priority. Outlined below are some of the key factors that have emerged as effective elements of a residential marketing strategy.

All-Solar Subdivisions

Purchase of an isolated solar building requires a statement of faith unlikely in any but an early innovator. By contrast, clusters of passive solar buildings signal a trend and give evidence to a degree of societal acceptance necessary to most people undertaking a large financial obligation. Rather than feeling like a loner, the buyer becomes part of a trend along with his neighbors.

Another key advantage to a solar subdivision is that the developer controls the siting of all buildings and can even write in covenants protecting solar access.

Site Planning and Development

With a little forethought, good solar access can be planned into a development from the beginning with no loss in density. Two basic stratogies have been used. In the first, a normal rectilinear grid system is used with the street spacing east-west generally somewhat greater than the spacing north-south. The lots with the buildings facing the street on the south can be somewhat shallower and wider, having good solar access because of the street. The lots with buildings facing north on the street need to be somewhat deeper and, therefore, somewhat narrower to obtain comparable solar access through their back yards.

A second procedure is more applicable to a planned unit development and creates a more interesting neighborhood and a more creative atmosphere for site planning. Streets are run into the individual lots from the north, locating garages on the north side of the house with good solar access preserved to the south.

In both of the above plans, it is appropriate to put covenants or zoning restrictions on the property that guarantee solar access to every building. Also, streets should be narrow and shaded to minimize the summer heating effect, vegetation should be located both to the east and west of the buildings to provide for summer shading and not winter shading, and good account should be made of prevailing summer winds through the site to provide natural ventilation.

High Solar Fractions

If a building is to be labeled passive solar, it should indeed be so. The solar savings (compared with a nonsolar building having the same floor area and with comparable energy conservation measures) should be at least 40% in cloudy climates or 60% in sunny climates, and the corresponding actual solar heating fraction should be 55% and 70%, respectively. Such a building is demonstrably and visually a solar building and no apologies need to be made at a later time.

Balanced Conservation and Solar

If a building is to meet all of the other objectives listed, it must combine good conservation practices with the solar strategies. This means a consistent application of good insulation practices and low air infiltration. Whether achieved by detailed analysis or simply by adherence to good design guidelines, a proper mix of conservation and solar should be achieved. If this is not done, the required solar collection area will be too large, thermal mass requirements for adequate heat storage will be too great, control will be difficult, and the building will probably not be economic.

Good Thermal Comfort

Thermal comfort implies stable interior temperatures. The building should have small temperature swings under free running conditions, that is, during times when no back-up heating is required to maintain the building inside temperature within the comfort zone. This is perhaps the most stringent of all the requirements because it means that the building must have adequate thermal mass for heat storage, a proper relationship between location of solar gains and heat storage, and effective heat distribution. However, without these essentials, the building will not create the type of internal environment necessary to assure adoption of passive solar buildings on a wide scale.

Residential Daylighting

The use of natural light provides the major rationale for passive solar heating in commercial buildings. However, even in residential situations, daylighting is an important aspect of design. Natural light adds character and livability to the design as well as replacing the need for most artificial lighting during the day. Dark and uninviting interiors can be avoided by the proper use of windows. By stressing the multifunction use of windows for lighting, passive solar heating, emergency egress, and ventilation, the window is made to pay for its extra cost in many ways. Skillful use of windows becomes a major design element.

High Quality of Construction

By adherence to the principles outlined above, the designer will have already integrated thermal quality into the building. It is only consistent to follow this up with use of good materials and high quality of construction to assure a building that is viable over the long term. Prospective buyers will look for this consistency and readily detect inconsistencies. The project must manifest quality from site planning through final execution.

The increasing cost of building creates enormous pressures to compromise on any or all of the above ingredients in favor of lower cost. An even stronger element, however, is the fact that people are economically unable to move as often as in the past and, thus, are deciding to buy for the longer term. It makes little sense to undertake a major thermal retrofit of a building only 5 to 10 years after its completion; such a retrofit will be much more expensive than if the thermal quality had been designed in from the beginning and its effectiveness will likely be much less. Citing recent practice is an inadequate excuse for perpetuating the poor habits of the past. We now know how to make buildings that use only 10 or 20% as much energy as typical contemporary buildings, and the inherent longevity of all buildings places an obligation on us to make the most of this knowledge.

Costs

Typically, the passive solar features will add 5 to 10% to the initial construction cost of a building. The added cost is usually in the range of \$53-\$106 per annual GJ of energy savings (\$50-\$150/annual million Btu savings). This leads to simple payback times in the range of 5 to 15 years when compared with alternative methods of heating.

Good Real Estate Basics

A solar building cannot be used to salvage a real estate project that is otherwise flawed. The developer must realize that real estate is a local process, responsive to local requirements, that standards are set locally, that the demand and building styles are governed by local considerations, that the market segment being addressed must be matched to the building and passive solar system being employed, and that it is ultimately the reputation of the builder that is the basis for a continuity of sales that mark success in a cyclical market.

Multifamily

Only a few multifamily passive solar buildings have been built. Most of these are two or three stories and are condominiums or townhouses where all of the above issues are important.

Commercial Practice

Although commercial passive buildings are far less prevalent than residential passive buildings, a large number have been built. The design issues are quite different, not only because of the importance of daylighting, but also because the character and time of use are different. The most frequent applications have been in schools, with the next most frequent in small office buildings. These have seemed to be quite successful, although there have been few results available from monitoring.

The few large passive projects have been the subject of intensive investigation by teams of architects and engineers. The design issues are complex and are outlined in some detail, together with several case histories, in Ref. [25].

The key issues to be considered in commercial buildings are as follows:

1. Creating a better working atmosphere. Windows, with the daylighting and ambiance they provide, are the key element.

2. Reducing peak utility loads. Commercial property is usually billed by an electric utility company both for consumption (kWh) and for the monthly peak demand (kW). Often the latter is the larger expense, particularly in the summer months. The combined effect of reduced lighting loads and the resulting reduced cooling loads can represent a large savings. Mass in the building can help by absorbing heat that shifts cooling loads later in the day, perhaps until they can be met by night-vent cooling.

3. Reducing energy consumption. Note that this is listed last because it is often the least important of these issues.

Retrofits

Passive solar additions or renovations to existing buildings have proven to be a very important part of passive practice, especially in the residential sector. Perhaps one-half of the total number of applications have been retrofits. The most important strategies employed are as follows:

- Adding south-facing windows. This provides additional direct gain to a structure that may have very adequate thermal mass built in, especially if it is an older building.

- Adding a solar greenhouse. The attached solar greenhouse is proving to be a very popular addition, as much because of the added food-growing potential, natural winter humidity, and ambiance provided as for the extra heat.

- Adding a convective-loop air heater outside an existing south-facing insulated wall. These are lightweight and inexpensive and are especially effective because they can be built to shut off at night by means of a simple passive backdraft damper. They can be used on apartments or other multistory structures.

- Glazing an existing south-facing masonry wall. Thermocirculation vents can be cut through or not as desired, depending on whether the building currently requires major daytime heating.

A particular advantage to passive solar retrofit applications is that one can do a little or a lot or do several small additions in sequence.

The Building is the Product
With active solar systems, as with other heating, ventilating, and air-conditioning systems, the designer is adding equipment to a building to serve a thermal function. Passive design is different. The passive solar and thermal characteristics are integrated into the building design in a manner that almost defies their separation. Ideally, every component of the building serves multiple functions. The elements of shelter, heating, cooling, daylighting, heat storage, distribution, traffic, ambiance, and aesthetics become so intermingled that a designer must become a generalist, understanding each and melding them into a synergistic and cost-effective result.

SUMMARY

Research in passive solar heating is centered around the investigation of energy flow in buildings, emphasizing the collection, storage, and distribution of solar gains, and the extent to which these effects can reduce the need for auxiliary heat within a building. Far from being esoteric research, it has been highly motivated to produce results that are of direct relevance to building designers. Results of the research have found an eager audience among practioners of passive solar heating, and the translation of those results into design tools has been both rapid and effective.

The basic physics of energy flow in buildings is well understood, and the behavior of the basic passive solar heating types is very predictable given knowledge of the relevant solar and weather conditions and the factors that influence building load. It is doubtful whether further refinements and accuracy are warranted by the inherent uncertainties of weather and occupancy characteristics. These remarks apply to direct gain, thermal storage wall, and sunspace geometries.

For mixed systems and multizone situations, there has been less experimentation and analysis. Results from many buildings indicate, however, that there are not likely to be many surprises. Various passive solar strategies seem to work well together and complement one another effectively.

Exotic designs, with the exception of the double envelope concept, have not been carefully studied either analytically or experimentally. A variety of hybrid designs have been built in which air heated in one portion of the building (frequently a sunspace) is ducted either through a rock bed or through holes formed in the masonry structure of the building. These seem to have worked well, but there has been little generalized investigation.

To date, passive solar design has consisted largely of reconfiguring traditional building elements to make more effective use of the building for the collection, storage, and distribution of solar heat function. There has been little research into improving those elements so that they might better serve these functions. Recent systems analysis[26] has indicated that net performance can be approximately doubled through the use of elements with improved thermal and optical characteristics.

Continued research can be expected to play an important role in the future development of passive solar heating. Areas of particular importance are materials research, building evaluations, and performance analysis.

Materials research and development can play a significant role in developing new products or variations on old products that will significantly improve thermal performance and comfort. The area offering the greatest opportunity for improvement is in glazings and apertures. It should be possible to improve transmittance, to greatly reduce heat loss, and to increase the controllability of the aperture. It may also be possible to more effectively utilize opaque sections of the building skin for solar collection.

Improvements in heat-storage characteristics of the building will probably be realized largely through improved use of conventional materials within the building obtained through a better understanding of the role of building configurations on heat storage and distribution. Although phase change materials remain an ever-popular field for research effort, they have had negligible impact on the utilization of passive solar heating to date.

The most important role of building evaluations is in the assessment of the effectiveness of techniques under field trial. There seems to be no lack of ideas being tried by inventors and it is important that these ideas receive a fair and dispassionate evaluation.

Performance prediction, based on sound physical principles, is essential if passive solar heating is to develop in an orderly fashion. Research results combined with practical experience will merge into design tools that are simple to use but comprehensive enough for widespread application. Intuition plays an important role in the evolution of new concepts, but it is only through the application of scientific techniques that research can sort out wishful thinking from sound and effective methods.

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